Capillary Flow Experiments

Science Requirements Document

ZIN Technologies

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Approvals

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Abstract

NASA is constructing a series of handheld test vessels to study key characteristics of low-g capillary flows aboard the International Space Station (ISS). The Capillary Flow Experiment (CFE) consists of 6 approximately 1 to 2 kg test vessels designed to probe certain capillary phenomena of fundamental and applied importance, such as: capillary flow in complex containers, critical wetting in discontinuous structures, and large length scale contact line damping. Quantitative video images from the simply-performed flight experiment crew procedures will provide immediate confirmation of the usefulness of current analytical design tools, as well as provide guidance to the development of new ones.

1. Introduction

1.1 Motivation

Capillary flows and phenomena are critical to myriad fluids management systems in low-g: fuels/cryogen storage systems, thermal control systems (e.g., vapor/liquid separation), life support systems (e.g., water recycling), and materials processing in the liquid state. In fact, NASA's near term exploration missions plan larger liquid propellant masses than have ever flown on interplanetary missions. Under microgravity conditions, capillary forces can be exploited to control fluid orientation so that such large mission-critical systems perform predictably. The Capillary Flow Experiment (CFE) presented here is a simple fundamental scientific study that can yield quantitative results from a safe, low-cost, short time-to-flight, handheld fluids experiment. The experiments aim to provide results of interest to the capillary flow community that cannot be readily achieved in ground-based tests. Specific applications of the results center on particular fluids challenges concerning propellant tanks. The knowledge may help spacecraft fluid systems designers increase system reliability, decrease system mass, and reduce overall system complexity.

CL

Two Capillary Flow units are proposed to study a fundamental and practical concern for low-g fluid phenomena: the impact of the dynamic contact line on large and small amplitude free surface oscillations. The contact angle is the macroscopic wetting angle of a particular fluid/fluid/solid system. The contact angle is defined from the line tangent to the interface at the "contact line." On a microscopic scale the contact line actually represents the region where the two fluids and solid coexist. From a macroscopic point of view, this region reduces to a "line of contact" (contact line) for the system. Both contact angle and contact line are represented schematically in Fig. 1 for a low-g interface in a right circular cylinder.

Because very large amounts of fluid are dominated by capillary forces in low-g environments, The contact angle and contact line can dominate the interface shape, which in turn controls interface dynamics and stability—critical issues for fluids management in space and spacecraft control. Fundamental questions remain concerning the physics of the moving contact line and insights that can be gained from low-g experimentation are welcome, particularly as regards the larger interfaces that arise there that can not be readily tested using terrestrial experimental methods. The two Contact Line (CL) units investigate natural and higher order linear and nonlinear oscillations, damping, and stability to a variety of disturbances (i.e. slosh, swirl, etc.). The response of the fluid is measured for both pinned and free contact line boundary conditions for a perfectly wetting and partially wetting fluid.

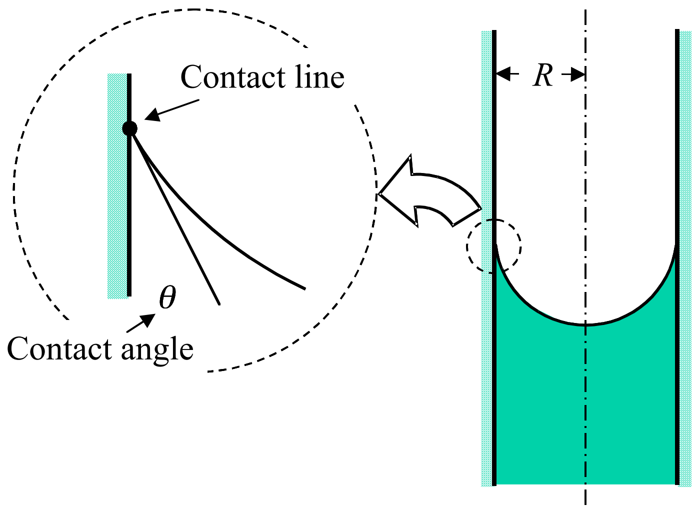

Fig 1. Low-g interface shape in a right circular cylinder identifying both contact angle and Contact Line (CL).

ICF

The Interior Corner Flow (ICF) experiment seeks to determine the rates of 3-D imbibition of wetting fluids in complex containers. On a local level, the initial wetting rates of such flows are fast and can be studied using drop towers. However, a slow migration ('secondary imbibition') of fluid across the chamber driven by the combined effects of capillary forces and global changes in container dimensions can only be studied in the long duration low-g environment of the ISS. The test cells can be constructed to be orders of magnitude larger than such systems on Earth—significantly altering the time scales of the flow and dramatically increasing the volume of fluid involved. The experiments are designed to benchmark the analytical technique developed to predict such flows. The benchmarked theory can then be used to design and analyze capillary devices for positioning liquids passively in containers in low-g environments by careful control over container geometry (i.e. passive control of water processing). The devices can also be used to perform passive phase separation operations such as in the case of tapered screen galleries for bubble-free collection and positioning of fuels for satellites, an important and outstanding problem for propellant management aboard spacecraft.

VG

The Vane Gap (VG) experiment seeks to identify a fundamental wetting condition akin to the critical corner wetting condition identified by Concus and Finn (1969), but for interior corners formed by walls that possess a gap at the virtual axis of intersection of the two planar walls (i.e. vanes). Such a "wall-vane gap" is common in spacecraft systems, but is treated as an ideal corner. The impact of this condition on systems exhibiting partial wettability is expected to be significant, with immediate implications to the design of passive techniques to manage aqueous solutions (i.e. water processing). The unique vane gap critical wetting phenomena has been computed numerically for the cases proposed for investigation, but has not been verified by experiment or theory. The numerical methods to compute such behavior are themselves without sufficient validation and the experimental results will serve in this respect. The experiment focuses on the establishment of equilibrium, which requires ample low-g time as well as small amplitude perturbations to assure local stability. The experiment is ideally suited for hand operation by a crewmember and builds on the heritage of similar experiments flown on the space shuttle (i.e. ICE exotic, ICE proboscis).

1.2 Scientific Objective and Significance

CL

The primary objective of the CL unit experiments is to identify the extent the role of the boundary condition at the contact line plays in the natural dynamic response of a large capillary interface to a variety of disturbances. This is accomplished via two identical, closely and rigidly coupled, partially filled right circular cylindrical containers; one that allows nearly perfect slip at the contact line and one that exhibits nearly perfect "stick" at the contact line (pinned contact line). The disturbances may be imparted by hand, and the interface response recorded by video camera. Perfect and partially wetting fluids will distinguish the two CL units. A secondary objective is to observe long time scale passive phase separation in containers with wettability gradients.

Because the cylinders are so closely and rigidly coupled, disturbances to the modules will produce quite similar disturbances to the fluid in both of the cylinders. Frequency and damping rate will be measured from the video recordings. Comparisons of the data for a variety of disturbances will clearly identify the bounds that can be expected for the assumptions of free and pinned contact lines.

ICF

The primary objective of the ICF units is to experimentally determine secondary imbibition rates in complex containers due to spontaneous large length scale capillary flows along interior corners in weakly 3-dimensional containers. Secondary objectives of the experiments are to quantify such flows in closed loop cycles, and to identify the passive phase separation characteristics of certain capillary driven multiphase-flows (e.g. bubbly flow) along interior corners. The experimental results will be used to verify or further guide current theoretical predictions.

Spontaneous capillary flows in containers of increasing complexity are currently under investigation to determine important transients for low-g propellant management. Significant progress has been made for complex containers that are cylindrical, but many practical systems involve containers/geometries that are tapered. The taper provides particular design advantages in preferentially locating the liquid where desirable. Flow in such containers is called imbibition and cannot be tested on the ground for 3-D geometries with 'underdamped fluids'—a most common characteristic of low-g fluid systems. The equations governing the process are known but have not been solved to date because of a lack of experimental data identifying the appropriate boundary conditions for the flow problem. Long-duration low-g experimental results will guide the analysis by providing the necessary boundary condition(s) as a function of container cross section and fill fraction.

VG

The primary objective of the VG units is to determine equilibrium interface configurations and critical wetting conditions for interfaces between interior corners separated by a gap. Perfectly and partially wetting fluids will be tested. A secondary objective is to validate numerical predictions of the large length scale discontinuous or nearly discontinuous wetting phenomena.

In a strict sense, the Concus-Finn (1969) critical wetting condition is radically altered for interior corners that do not actually contact; such as in the gap formed by a vane and tank wall of a large propellant storage tank (a commonality in practice), or the near intersection of vanes in a tank with complex vane network. The VG experiments will test a variety of vane-wall conditions. Vane gap and vane-wall angle will be varied repeatedly sweeping about both sub- and super-critical wetting regimes as well as the wetting hysteresis map. The container consists of a test vessel with a vane that can be pivoted changing both the angle of the vane and the wall and the size of the vane-wall gap. The vane is slightly asymmetric so that two ‘gaps’ can be tested for each container. After injecting the prescribed amount of fluid the crewmember rotates the vane at set intervals allowing significant time (up to 5min.) for the fluid to equilibrate between each interval. Static interface shapes recorded by video will be compared quantitatively with numerically computed shape. At a critical vane angle the fluid will spontaneously wet the corner at which point the vane angle will be measured for comparison to theory.

1.3 Justification for Extended Microgravity Environment

CL

The contact line experiment requires perturbations to quiescent low-g interfaces. Such interfaces require several seconds to form and preclude the use of drop towers for study. Large amplitude perturbations to such interfaces require several seconds to impart to the containers and subsequent damped oscillation can require up to 45s to decay—thus, the total low-g experiment time can be as high as approximately 60s per single perturbation (e.g. the ‘swirl’ perturbation). On the order of one hundred perturbations are requested for the CL units. Even for tests that could exploit the approximately 25s of low-g time afforded by aircraft, experimentally imposed perturbations on the order of $\pm 10^{-1}$ to 10^{-5}g imparted to the vessel could not be distinguished from the uncontrolled and unsteady background acceleration environment of the aircraft. Thus, ground based facilities are incapable of generating the database required for the CL experiments.

The largest interface possible is selected for the test, which is limited by experiment mass and fluid volume constraints for the CFE experiments. The larger the interface, the more applicable the results are to realistic systems; the longer the interface relaxation times are, the stronger the need for long duration microgravity conditions. Relaxation times for interface oscillations in the fuel tanks of orbiting space craft, with a characteristic length ~ O(1m), require upwards of 45 minutes to decay, or may in fact never decay due to low level g-jitter. A secondary objective for the CL units investigates bubble migration and separation due to wettability gradients along container walls. This process is predicted to require approximately 5 minutes per trial. In addition to these requirements for the long duration low-g time afforded by the ISS, the astronaut interface is invaluable for noting unusual fluids behavior in real time and responding by altering or extending tests in the extra science portion of the crew procedures.

ICF

Large capillary length scale imbibition in containers with interior corners occurs in two phases. The primary initial phase is characterized by high flow rate wetting of the interior corners of the vessel that is followed by a slow exponential-like creep toward the eventual steady equilibrium state. 3-D container effects control the secondary phase of the imbibition, which can be extremely weak in the case of tapered containers of significant application potential for the passive positioning of large quantities of fluid in low-g fluid systems. For the 'large and under-damped' ICF units, the expected experiment duration to capture the secondary geometry dependent imbibition rates exceeds 15 minutes. This time is longer than other low-g facilities such as a drop tower and aircraft can provide. Manifold tests of this nature require several hours of continuous low-g.

VG

The general procedures for the VG units are nearly identical to similar handheld ICE experiments performed on the space shuttle (Concus et al. 2000) and Mir space station (Concus et al. 1999). Approximately 1 minute of unperturbed low-g time is necessary to achieve an initial equilibrium interface condition. (Approximately 5 min. are required for fill of the test container on orbit.) At each adjustment of the vane angle a period of 1 minute is required to re-establish equilibrium followed by a series of finger taps and pauses to assure local equilibrium. This procedure is time consuming, but necessary to establish the experiment requirements. Several hours of low-g time are requested for such experiments, which obviously cannot be achieved using ground-based facilities. The experiment also cannot be miniaturized without strongly amplifying the effect of surface irregularities, which are not present nor representative of the large length scale capillary phenomena achievable in the low-g environment.

This is experiment is unique to the low-g environment because sufficient low-g time is available to assure local equilibrium, but, and more importantly, because it can be reversed and repeated (potentially sweeping out a hysteresis band) providing data for a common and uninvestigated problem while serving as a complex benchmark problem for numerical solutions.

1.5 Literature Review

CL

Salzman (1969) studied low-g slosh dynamics using a 5s drop tower and characterized natural frequency and logarithmic decrement for a variety of systems. Significant work has focused on sloshing in tanks beginning with Dodge (1991). The particular impact of the contact line boundary condition on capillary oscillations has been identified Hocking (1987), but a clear demonstration of the difference of contact line conditions on fluid behavior has not been made. Flight experiments of linear or other surface oscillations have been conducted at least by Dodge (1991), Van Schoor (1992) and by Allen (1996). Weislogel and Ross (1990) reported 2.2 second drop tower data for axial mode perturbations in the range of $0.00146 = Oh = 0.0440$, where Oh is the Ohnesorge number[*]. They established correlations for natural frequency and settling time as a function of Ohnesorge number and equilibrium contact angle. Wölk, et. al. (1997) published a numerical analysis of damped oscillations of a liquid/vapor interface after a step reduction in gravity using a commercial code and showed a wide range of predictions depending on the contact line boundary condition (free or pinned). Michaelis et al. (2003) conducted further and conclusive low-g studies and analysis for large contact angle, linear, axial mode oscillations.

ICF

Recent solutions to capillary driven flows in containers with interior corners provide the foundation from which to extend the predictive capabilities to flows in weakly 3-D containers, such as the tapered polygonal containers of the ICF. Some of these solutions are recently summarized by Weislogel (2003). A quasi-steady solution can be derived for the imbibition in the ICF containers using solutions yet to be published (Weislogel, 2004). No experimental verification of the theory has been attempted to date in the low-g environment.

VG

The original critical corner wetting theory was established with mathematical rigor by Concus and Finn (1969). Chen and Collicott (2002) recently provide drop tower data that is suggestive of a similar critical wetting condition for corners separated by a gap. The critical condition is predicted using the *Surface Evolver* algorithm (Brakke 2003) and includes the complicating effects of gap size and vane thickness. Vane-wall curvature is also an appropriate consideration in light of the fact that most vane gaps are formed between straight vanes and curved walls. The dynamics of capillary driven flow within interior corners possessing a gap are currently under study as a special case of study on non-idealized (i.e. rounded) corners and a paper has been accepted for presentation on the subject (Chen and Weislogel 2004).

4. Experimental Flight Plan

4.1 Rationale

CL

The CFE-CL experiment is a difference experiment that isolates two extremes of a single variable, the contact line boundary condition, for uniquely low-g interfacial phenomena of fundamental and applied interest.

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[*] *The Ohnesorge number is a relative measure of the inertial forces in a capillary flow. It is typically defined as:* $Oh = (\rho \nu^2 / \sigma R)^{1/2}$ *where* ρ *= fluid density,* ν *- fluid kinematic viscosity,* σ *= surface tension, and R is a characteristic length (i.e. cylinder radius) .*

ICF

The CFE-ICF experiment quantifies the nature of large length scale capillary flows throughout 3-dimensional polygonal containers for the purpose of theory development and verification. Applications of the results are immediate for the design and analysis of passive fluids managements system for spacecraft (i.e. liquid fuel/oxygen storage tanks).

VG

The CFE VG experiments investigate a fundamental, geometric critical wetting condition that occurs in complex systems.

4.2 General Specifications for CFE

CL

Simultaneous unimpeded profile imaging is required of two identical fluid interfaces in right circular cylindrical containers, recording the response of the liquids to a variety of disturbances imparted by hand. (Unimpeded imaging implies imaging essentially free of artifacts due to effects such as significantly non–uniform lighting, stray reflections, etc.) The difference between the two interfaces is only that one is free to slide along the container wall and the other is pinned on an edge.

ICF

Unimpeded imaging of a variety of transient capillary driven flows in tapered containers of polygonal section is required. (Unimpeded imaging implies imaging essentially free of artifacts due to effects such as significantly non–uniform lighting, stray reflections, etc.) The capillary transport of liquid throughout the containers will be compared to theoretical predictions.

VG

Unimpeded imaging of a fluid interface in right elliptical cylindrical containers following the rotation of a planar vane along the axis of the cylinder is required. (Unimpeded imaging implies imaging essentially free of artifacts due to effects such as significantly non–uniform lighting, stray reflections, etc.)

4.3 Sequential Test Plan

CL

In all, 7 separate 'disturbance-types' must be imparted for the CL investigation. the first uses the normal background g-jitter level of the ISS: the remaining disturbances are named: Tap, Push, Slide, Swirl, Displacement, and Bubbles. All of the disturbances require imaging resolution of the interfaces to approximately 0.20mm except Bubble, which should exploit a larger FOV and approximately 0.50mm is acceptable. For all tests, it is requested that fluid interface behavior deemed interesting to the crew be repeated if possible—time and resources permitting.

General Notes, applicable to all tests:

General procedure and cautions are identical for both CL1 and CL2.

Caution Notes, applicable to all:

The disturbances are imparted beginning with weak forces and increasing in strength over time. Care should be taken not to prematurely destabilize the pinned surface, which would reduce the quality of comparisons between pinned and free contact line conditions—the basis of the experiment.

I. Background

The objective of the Background test is to get the background g-jitter signature imparted by ISS on the fluid surfaces. The surface response to the ISS g-jitter environment should be recorded for 20min.

II. Tap

The objective of the Tap tests is to observe the differences in dynamic response of the surfaces to small amplitude impulse-type disturbances of increasing amplitude (linear). The solitary Taps should begin very lightly and increase over time, but never to the point the pinning cylinder interface is destabilized or the fluid interfaces break up or bubbles form. Ample time should be allowed after each Tap for the disturbance to decay. Each Tap should be identified when applied (i.e. by video or audio). The Tap disturbances will excite predominantly axial mode oscillations.

III. Push

The objective of the Push test is to observe the differences in dynamic response of the surfaces to laterally induced impulse-type disturbances of increasing amplitude (linear). The solitary Pushes should begin very lightly and increase over time, but never to the point the pinning cylinder interface is destabilized or the fluid interfaces break up or bubbles form. Ample time should be allowed after each Push for the disturbance to decay. The Push disturbances will excite predominantly slosh mode oscillations. Amplitudes of between 5 to 30mm should be applicable.

IV. Slide

Slide is perhaps the most important test. It is advantageous not to have inadvertently depinned the pinned interface prior to completion of all Slides. The objective of the Slide tests is to observe the differences in dynamic response of the surfaces to laterally induced oscillatory-type disturbances of increasing amplitude (linear to nonlinear). A Slide is a single or multiple period lateral oscillation of the interfaces at the approximate natural frequency which may vary for nonlinear disturbances. Termination of the Slide results in damped oscillations of both interfaces at their respective (and approximately equal) natural frequencies. The Slide approximate amplitude should be able to be varied between 5mm and 30mm. The number of Slide cycles should be variable from 1 to 4 full periods.

V. Swirl

The objective of the Swirl test is to observe the differences in dynamic response of the surfaces to swirling slosh mode disturbances of increasing magnitude and vorticity. Such a Swirl may be induced by hand into the fluid using an elliptical or circular sliding motion of the CL in a plane normal to the cylinder axes. A Swirl disturbance diameter is based on the natural frequency and will be determined by the crew during operations. It is expected to be no greater than 30 to 40 mm. The number of swirl cycles per Swirl disturbance will vary from 1 to 4 full cycles and swirl amplitudes may vary between 5 to 40mm. All Swirl disturbances should be imparted at approximately the natural swirl frequency of the fluid. Ample time should be allowed after each Swirl for the disturbance to decay.

VI. Displacement

Displacement is the first disturbance where depinning of the pinned interface is desired. The objective of the Displacement tests is to observe the differences in dynamic response of the surfaces to laterally induced large amplitude deflections of the interface of increasing amplitude (nonlinear). A Displacement (rapid-push) is accomplished by hand using a fairly rapid lateral translation of the CL to the degree that the pinning interface is destabilized. Interface disturbances caused by Displacement are large and require more time to damp out (up to three minutes predicted). Termination of the Displacement results in a slow recovery to equilibrium which will vary between smooth and pinned cylinders. The Displacement disturbance amplitude increases with each Displacement, but not to the point large portions of the fluid are separated from the bulk. In the case of inadvertent reorientation of fluid to the lid or sidewalls of the CL cylinders a means of returning the fluid to the base must be available to continue with the tests. The slow coalescence process will be recorded on video using a larger (approximately 2-fold) FOV than the previous tests I—V above.

VII. Bubbles

The objective of the Bubble test is to observe the differences in bubble coalescence rates between the two cylinders for identical disturbances. Bubbles are created by shaking the CL. At first only a small number of large diameter Bubbles should be developed via light agitation with larger numbers of smaller bubbles generated during subsequent tests via more vigorous agitation. The slow coalescence process will be recorded on video using a larger (approx. 2X) FOV than the previous tests I—V above.

Test Matrix

Test Name	Tap	Push (mm)	Slide (mm)	Multi-Slide (amp. mm)	Swirl (#cycles)	Displacement	Bubble

Background	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Run 1 (Repeat)	Tap	10	10	10	1	Displace	1-3
Run 2 (Repeat)	Increase	15	15	15	2	Increase	10-20
Run 3 (Repeat)	Increase	20	20	20	3	Increase	25-35
Run 4 (Repeat)	NA	25	25	25	4	Increase	50-60
Run 5 (Repeat)	NA	30	30	30	5	Increase	>60 (foam)

ICF

<u>General Notes, applicable to all tests</u>:

The two units are CFE-ICF1 (equilateral triangular section) and CFE-ICF2 (rectangular section). The test sequence has the following general procedure:

Fluid is fairly rapidly delivered from a fluid reservoir to the base of the tapered test chambers.

1. <u>Initial Fill</u>. In the low-g environment the liquid will imbibe throughout the container. This and the processes to follow are captured on video.
2. After the initial imbibition is complete (fluid shifts to top of container and equilibrates), the apparatus should then be able to repeat the previous test up to three times. The first test results in a flow over initially dry surfaces that cannot be repeated, but all subsequent repeat runs of the device will provide valuable data for pre-wet flow conditions which replicates a most common flow condition.
3. The apparatus should then be used to repeat the tests performed in (2), but allowing for a by-pass tube connecting the base of the tapered container with the top of the container. The tests conducted with such a by-pass line open simulate certain applications in microgravity fluids management systems and will provide another unique comparison opportunity for the theory established at present as fluid imbibes within the container as well as is drawn through the bypass line.
4. With the prescribed amount of fluid in the test chamber, bubbles should be generated in the chamber by ‘shaking’ the container. The container should be replaced for video photography, and the passive imbibition, phase separation and coalescence phenomena recorded. Such tests should be repeated at least once and several tests performed for a variety of bubble densities/sized and distributions.

Digitized video images will be compared to theoretical and numerical predictions.

<u>Caution Notes, applicable to all</u>:

After re/introduction of the fluid into the test chamber, sufficient time (up to approximately 15minutes) must be allowed for video photography of the redistribution of the fluid throughout the chamber.

VG

General Notes, applicable to all tests:

Two VG units are needed for the experiment to identify the impact of wetting on the critical wetting phenomena. The two units are in everyway identical except for the wetting condition and vane dimensions, CFE-VG1 (uncoated), CFE-VG2 (coated). The general experiment procedures for both vessels are identical and include:

1. A prescribed amount of liquid is dispensed from a reservoir into an elliptic cross-sectioned cylindrical container in the low-g environment.
2. The vane is then rotated clockwise through one complete revolution (360deg) in prescribed degree increments. The response of the fluid interface is recorded by video imaging.
3. At each increment of vane rotation, time (approximately 30s) is allowed for the interface to establish equilibrium. Small perturbations (by hand, i.e. finger taps) to the container should be employed to assure local equilibrium is established.
4. The vane rotation procedure is then reversed (counter clockwise) with identical increments and perturbations for the equilibrium surfaces.
5. The clockwise/counter clockwise rotation is repeated up to three times.

Caution Notes, applicable to all:

Special care must be taken during conduct of the experiments not to disturb the interface to the point the surface breaks-up and forms bubbles.

7. Success Criterion

Three mission scenarios are assumed here: (1) a nominal mission is where all originally proposed procedures are completed, (2) a minimum science/minimum success scenario is considered where minimal procedures are conducted from which at least one scientific observation can be made, and a (3) maximum (or extra) science scenario where additional tests are performed if additional crew time above that required for the nominal case were available.

7.1 Nominal/Minimal/Extra Mission Scenarios

CL

Nominal Mission Scenario:

The nominal mission scenario is one where all originally proposed procedures are performed and photographed. For the CL vessels this requires:

CL Vessels 1 and 2 identical

1. Set-up of vessel and lighting (~30-60min)
2. The complete displacement of fluid into each test cylinder. (~10-15min)
3. Perform background acceleration measurement.
4. A series of disturbances of increasing magnitude are imparted to the CL container by the crew until the interface breaks-up.
5. Return of flight video tapes.

Minimal Mission Scenario:

The minimal mission scenario is one where only one disturbance event is photographed that could provide data that could be used to verify predictions or assist in the design of low-g fluids systems. For the CL Vessels this could entail:

CL Vessels 1 and/or 2 (CF2, no coating, has higher priority)

1. Set-up of vessel and lighting (~30-60min)
2. Filling of both cylindrical chambers and observation of damped surface oscillations after several disturbances imparted to the container by the crew member. (~15-20min)
3. Downlink of video data (minimum) or return of flight video tapes.

Extra Mission Scenario:

The extra mission scenario is one where additional time and resources (video tape) are available to perform tests that can yield quantitative science or engineering information in addition to that gained from the successful performance of the nominal mission. [Experiments Procedures VI Displacement and VII Bubbles might be considered Extra Science as well as further experiments performed say in 'Saturday Science Mode' aboard the ISS.] Several possible extra tests are valued, and such tests using CL-1 would be of highest priority.

CL Vessels 1 and 2

1. Repeat the nominal mission scenario for this two-interface configuration. (~30-40min)
2. With liquid volume fully dispensed into chambers, detach the CL vessel from the support and excite axial mode oscillations in the fluid, replacing the vessel on the test stand and photographing re-establishment of steady conditions. (~1min per event)
3. Test liquid depth effects by incrementally reducing pinned cylinder volume by 25% and repeating several multiple slide disturbances.
4. Time elapsed photography of ISS g-jitter on bubbles formed.
5. Others can be specified such as axial mode perturbations.
6. Return of flight video tapes.

ICF

Nominal Mission Scenario:

The nominal mission scenario is one where all originally proposed procedures are performed and photographed. For the ICF vessels this requires:

ICF Vessels 1 and 2 procedures and tests are identical

1. Set-up of vessel and lighting (~30-60min)
2. The filling of test chamber and observation of capillary driven flow from the base to top of the container. (~20min)
3. Repeated draining and refilling of the test chamber with and without bypass tube. (80-120min)
4. Conduct and repeat Slosh and Bubble Shake tests.
5. Return of flight video tapes.

Minimal Mission Scenario:

The minimal mission scenario is one where only one disturbance event is photographed that could provide data that could be used to verify predictions or assist in the design of low-g fluids systems. For the CL Vessels this could entail:

ICF Vessels 1 and/or 2 (ICF1 has higher priority):

1. Set-up of vessel and lighting (~30-60min)
2. The filling of test chamber and observation of capillary driven flow from the base to top of the container. (~20min)
3. Repeated draining and refilling of the test chamber with (once) and without (once) bypass tube open. (40min)
4. Downlink of video data (minimum) or return of flight video tapes.

Extra Mission Scenario:

The extra mission scenario is one where additional time and resources (video tape) are available to perform tests that can yield quantitative science or engineering information in addition to that gained from the successful performance of the nominal mission. [The first fill test cannot be repeated. However, all other experiment procedures can be performed in 'Saturday Science Mode' aboard the ISS.] Several possible extra tests are valued, and could use either ICF vessel (or both). Result from onboard testing would play a significant role in identifying a priority for extra science should such an opportunity arise.

ICF Vessels 1 and/or 2 (ICF1 has higher priority)

1. Repeat the nominal mission procedures. Statistical results are possible for this experiment. (~30-40min)
2. Time elapsed photography of ISS g-jitter on bubbles formed.
3. Others could be specified such as more complex phase separation tests.
4. Return of flight video tapes.

VG

Nominal Mission Scenario:

The nominal mission scenario is one where all originally proposed procedures are performed and photographed. For the VG vessels this requires:

VG Vessels 1 and 2 procedures are identical

1. Set-up of vessel and lighting (~30-60min)
2. The filling of the elliptical cylindrical test chamber. (~10-15min)
3. Rotation of the vane 360deg CW and CCW. (~40-60min)
4. Two repeat rotations of the vane (40-60min)
5. 720deg continuous rotation both CW and CCW (10min)
6. Return of flight video tapes.

Minimal Mission Scenario:

The minimal mission scenario is one where only one complete 360 CW and CCW rotation of the vane is completed. For the VG Vessels this could entail:

VG Vessels 1 and 2 (VG1 higher priority)

1. Set-up of vessel and lighting (~30-60min)
2. The filling of the elliptical cylindrical test chamber. (~10-15min)
3. Rotation of the vane 360deg CW and CCW. (~40-60min)
4. Downlink of video (minimum) or return of flight video tapes.

Extra Mission Scenario:

The extra mission scenario is one where additional time and resources (video tape) are available to perform tests that can yield quantitative science or engineering information in addition to that gained from the successful performance of the nominal mission. [All experiment procedures for VG can be performed in 'Saturday Science Mode' aboard the ISS.] Extra tests are valued, and could use either VG vessel (or both). Results from the nominal onboard testing would play a significant role in identifying a priority for extra science should such an opportunity arise.

VG Vessels 1 and 2

1. Repeat the nominal mission procedures. Statistical results are possible for this experiment. (~40-120min)
2. Rotate the vane at several steady rotation rates through 720 degrees CW and CCW. Rotation rates should start slow and increase incrementally up to approximately 1Hz.
3. Indexed rotation through 720deg at prescribed increments, CW and CCW.
4. Time elapsed photography of the interface at a slightly subcritical wetting condition.
5. Others could be specified.
6. Return of flight video tapes.

7. Science Requirements

CL

1. Cylinder diameter: 1.5”
2. Fluid: 2cs Si Oil
3. Cylinders are identical except for pinning lip
4. Depth of liquid to cylinder base for all cylinders is constant

CL-1 specifics;
1. Contact angle is 50º (interior surfaces are rinse coated with FC-724)
2. Height from base to pinning lip is 1.451”,
3. Volume of fluid is 39.04cc

CL-2 specifics;
1. Contact angle is 0º
2. Height from base to pinning lip is 2.0”
3. Volume of fluid is 43.44cc

7.1 Science Requirements Summary Tables

Table 1. Summary of Science Requirements - Contact Line (CL)

Parameter	**Section**	**Experiment requirements**
§5.2 Fluid and Fluid purity		
Working fluid		Silicon Oil [polydimethylsiloxane polymer] DC-200
Refractive index		1.3 – 1.6
Kinematic viscosity		2.0 cs
Volume of Fluid In test chamber		CL1 – 39.04 cc CL2 - 43.44 cc
§5.3 Test Cell & Test Cell Cleanliness		
Vessel geometry		Dual cylinders in each vessel
Number of vessels		2
Dimensions		1.5 inch diameter cylinders 2 mm pinning lip located: 1.451 inches above base for CL-1 2.0 inches above base for CL-2
test cell material		Plexiglas, visibly smooth polish
Interior wall coating		FC724 barrier coating: For CL1 == all interior surfaces For CL2 == lids and cylinder above pinning lip only
Test cell clarity and transparency		Visibly clean, clear and transparent
§5.4 Experimental Setup & Environmental Requirements		
Thermal Environment	§5.4.3	

Table 1. Summary of Science Requirements - Contact Line (CL)		
Parameter	**Section**	**Experiment requirements**
nominal temperature		Crew cabin temperature
Acceleration Environment	§5.4.4	MWA environment
g-levels during fill		= 2e-03g_o
Other Environment Requirements	§5.4.5	There are no known nor anticipated requirements for acoustic, electromagnetic, or radiation environments
§5.5 Experiment Control Requirements		
Telepresence	§5.5.3	Downlink initial results of experiment
§5.6 Experiment Data Requirements		
accuracy of resolution of camera		0.1 mm
FOV locations		During Fill: entire unit
		Background: fluid only
		Tap: fluid only
		Push: fluid only
		Slide: fluid only
		Swirl: fluid only
		Displace: fluid only,
		Baseline: fluid only
Temperature Measurements	§5.6.5	
Crew cabin air temperature		Before each experiment (± 1C) [If possible, remove unit from storage the day before running experiment, to allow adequate time for unit to equilibrate to the cabin temperature. As a minimum, record the time unit is removed from storage and the time first experiment run is started.]

ICF

ICF-1
1. Test cell: tapered 75-75-30 isosceles triangle
2. Height of vertex at base 1.575”
3. Height of vertex at top 1.024”
4. All faces taper at 3.155º
5. Test cell is 5” long
6. Fluid: 5cs Silicone Oil
7. Fluid volume is 10.00cc in test cell

ICF-2

1. Test cell: tapered rectangular section
2. Side faces taper only at 8.95º
3. Test cell is 5" long and 1.575" wide at base
4. Test cell is a constant 0.394" deep
5. Fluid: 2cs Silicone Oil
6. Fluid Volume is 9.02cc in test cell

Table 2. Summary of Science Requirements – Interior Corner Flow (ICF)

Parameter	**Section**	**Experiment requirements**
§5.2 Fluid and Fluid purity		
Working fluid		Silicon Oil [polydimethylsiloxane polymer] DC-200
Refractive index		1.3 – 1.6
Kinematic viscosity		5.0 cs for ICF1, 10.0 cs for ICF2
Volume of Fluid In test chamber		ICF1 – 10.00 cc ICF2 – 9.02 cc
§5.3 Test Cell & Test Cell Cleanliness		
Vessel geometry		Triangular (ICF1) and Rectangular (ICF2) sections
Number of vessels		2
Dimensions		Height of vertex at base 1.575" Height of vertex at top 1.024" All faces taper at 3.155º Test cell is 5" long
test cell material		Plexiglas, visibly smooth polish
Interior wall coating		None
Test cell clarity and transparency		Visibly clean, clear and transparent
§5.4 Experimental Setup & Environmental Requirements		
Thermal Environment	§5.4.3	
nominal temperature		Crew cabin temperature
Acceleration Environment	§5.4.4	MWA environment
g-levels during fill		= 2e-03g_o
Other Environment Requirements	§5.4.5	There are no known nor anticipated requirements for acoustic, electromagnetic, or radiation environments
§5.5 Experiment Control Requirements		
Telepresence	§5.5.3	Downlink initial results of experiment
§5.6 Experiment Data Requirements		

Table 2. Summary of Science Requirements – Interior Corner Flow (ICF)		
Parameter	**Section**	**Experiment requirements**
accuracy of resolution of camera		0.1 mm
FOV locations		Entire vessel test section
Temperature Measurements	§5.6.5	
Crew cabin air temperature		Before each experiment (± 1C) [If possible, remove unit from storage the day before running experiment, to allow adequate time for unit to equilibrate to the cabin temperature. As a minimum, record the time unit is removed from storage and the time first experiment run is started.]

VG

Two identical units, **CFE-VG1** (uncoated), **CFE-VG2** (coated):
(all dimensions in inches)

1. Ellipse Section: 2” by 1.333”. Height is 5”.
2. 1-g_o flat surface liquid fill level is 1.5” from base.
3. Vane dimensions:
   VG-1—1.234” by 0.079” by 4.5”
   VG-2—1.234” by 0.197” by 4.5”.
1. Vane pivot axis is coaxial with ellipse but gap dimensions are 0.033” and 0.066” when vane is aligned with minor diameter of ellipse. These gap dimensions represent a 0.95 and 0.90 dimensionless gap using the minor axis radius for normalization.
2. Vane angle rotation 360º with < 2.5º resolution
3. Contact angles are 0º (VG-1, no coating) and 60º (VG-2, FC724 coating).
4. Fluid is 10cs Si Oil. Fluid volume is 49.1cc.

Table 3. Summary of Science Requirements – Vane Gap (VG)		
Parameter	**Section**	**Experiment requirements**
§5.2 Fluid and Fluid purity		
Working fluid		Silicon Oil [polydimethylsiloxane polymer] DC-200
Refractive index		1.3 – 1.6
Kinematic viscosity		10.0 cs
Volume of Fluid In test chamber		VG1 – 49.1 cc VG2 – 49.1 cc
§5.3 Test Cell & Test Cell Cleanliness		
Vessel geometry		Elliptical test section with centered vane
Number of vessels		2

Table 3. Summary of Science Requirements – Vane Gap (VG)		
Parameter	**Section**	**Experiment requirements**
Dimensions		VG-1—1.234” by 0.079” by 4.5” VG-2—1.234” by 0.197” by 4.5”. Vane pivot axis is coaxial with ellipse but gap dimensions are 0.033” and 0.066” when vane is aligned with minor diameter of ellipse. These gap dimensions represent a 0.95 and 0.90 dimensionless gap using the minor axis radius for normalization.
test cell material		Plexiglas, visibly smooth polish
Interior wall coating		VG1 – no coating VG2 – FC724 coating
Test cell clarity and transparency		Visibly clean, clear and transparent
§5.4 Experimental Setup & Environmental Requirements		
Thermal Environment	§5.4.3	
nominal temperature		Crew cabin temperature
Acceleration Environment	§5.4.4	MWA environment
g-levels during fill		= 2e-03g_o
Other Environment Requirements	§5.4.5	There are no known nor anticipated requirements for acoustic, electromagnetic, or radiation environments
§5.5 Experiment Control Requirements		
Telepresence	§5.5.3	Downlink initial results of experiment
§5.6 Experiment Data Requirements		
accuracy of resolution of camera		0.1 mm
FOV locations		Entire vessel test section
Temperature Measurements	§5.6.5	
Crew cabin air temperature		Before each experiment (± 1C) [If possible, remove unit from storage the day before running experiment, to allow adequate time for unit to equilibrate to the cabin temperature. As a minimum, record the time unit is removed from storage and the time first experiment run is started.]

7. Ground Test Experimental Plan

7.1 Rationale

CL

Normal-g tests using the CFE-CL engineering units are essential for comparisons of the expected flight results. The tests will be essential for complete and quality publications as well as fundamental science. The engineering units can be provided to the PI on a schedule that does interrupt the critical path of development and flight qualification of the flight hardware. However, the ground tests must be conducted and preferably before the flight tests are performed so that the image analysis schemes can be developed for the subsequent flight experiments. The image analysis tools will be needed if real time analysis can guide subsequent tests during the mission. Simple drop tower tests could also be conducted for both axial and later slosh mode disturbances.

ICF

A series of drop tower tests (up to 20 drops, 2.2s tower GRC, 10 each vessel) should be performed to determine idealized wetting rates for the containers. Such results will guide development of the crew procedure, but will also produce new science. Further ground studies employing the ICF units can be used to investigate a unique and relevant low-g flow scenario for which an analytic solution is currently being pursued.

VG

A series of drop tower tests (up to 20 drops, 2.2s tower GRC) performed using the VG vessel would demonstrate the extent drop towers can be used to identify such critical wetting phenomena. It is almost certain that little could be learned from tests employing VG-2. However, tests using VG-1 are likely to guide the crew procedures in efficiently establishing appropriate near critical conditions, setting the increment of the vane dial, and optimizing the crew procedures. These tests could reduce crew time by honing in on the critical phenomena faster.

7.2 Ground Test Plan

A complete investigation for CL, ICF, and VG can benefit from a number of simple drop tower using the engineering CFE units. In several cases, new science can be gained increasing the breadth or impact of the flight results and enhancing their publication potential. In some cases, especially for the CFE-CL units, 1-g tests will be necessary to develop the image analysis tools necessary for (near) real time evaluation of the flight results to guide subsequent tests with the same vessel or a vessel to follow.

CL

In all 7 separate ‘disturbance-types’ must be imparted for CL and filmed in a 1-g environment: some background g-jitter environment, Tap, Push, Slide, Swirl, Displacement, and Bubbles. The data will be reduced and analyzed by the PI team. The disturbance amplitude, type, and frequency will be varied. The impact of both contact line conditions and fluid depth will be quantified to supplement the flight results. Drop tower test can also be performed investigating both axial and lateral mode oscillations and the impact of the contact line boundary condition.

ICF

The specific drop tower tests performed for the ICF units will be partly filling the test chambers and dropping them in the tower, recording the transient interface behavior on video. The tests serve as a more idealized initial condition for the flows to be achieved on orbit, which do not have the advantage of an 'instantaneous' fill process. The data will be compared to the flight results during the initial fill phases. Further important experiments will be conducted by inverting the test cells and dropping vessels. The transient capillary flows that result may be predicted by a recent similarity solution, but cannot be verified without such tests.

VG

Drop tower tests will be performed for VG1 for a variety of vane angles. The approximate range of the critical wetting phenomena will be identified and used to specify the vane increments for the flight experiment. There is not sufficient time to establish equilibrium in such experiments, but gross wet/no wet conditions may be identified. It is also possible to study specific flow rates for sub-critical angles where corner wetting is certain. Such flows constitute an important capillary driven flow in fluids management system on spacecraft: capillary driven flow along interior corners with gaps. The CFE-VG experiment investigates static behavior via a geometric critical wetting phenomenon. The latter drop tower experiments investigate also the dynamics of such flows, which would provide a complete story for publication of the investigation.

General Notes

The ground tests for the CL units could be conducted at NASA or at PSU by the PI team. All drop tower experiments CL, ICF, and VG should be conducted at NASA GRC's 2.2s drop tower facility by the PI team.

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